Neutron Measurements In Front of and Behind Shielding Using Bonner Spheres and Bubble Dosimeters

- **Measurements using Bonner Spheres**
  - ▸ ***Measurements inside of shielded vault***
  - ▸ ***Measurements outside of vault***
    - o **Outside of Concrete**
    - o **Outside of Iron**
- **Skyshine Measurements**
- **NSCL Capabilities**
  - ▸ ***Previous Work in Support of Space Applications***
  - ▸ ***Upgrade: Coupled Cyclotron Facility***

Int'l Workshop on Secondary Particle Production
LBNL, March 15-16, 2001
Reginald M. Ronningen
National Superconducting Cyclotron Laboratory
Michigan State University

Motivation for Measurements

- **NSCL proposed to upgrade its facility**
- **Couple K500 and K1200 Cyclotrons**
  - **Enhance radioactive ion beam capabilities**
  - **One particle-μA beams up to mass 36**
  - **Energies to 200 MeV per nucleon**
- **Shielding Design Ramifications**
- **Few data sets available for thick-target neutron yields, especially for heavy beams**

First results: G.I. Britvich, A.A. Chumakov, R.M. Ronningen, R.A. Blue, and L.H. Heilbronn, Review of Scientific Instruments **70**, 2314(1999), (erratum) **72**, 1600(2001).

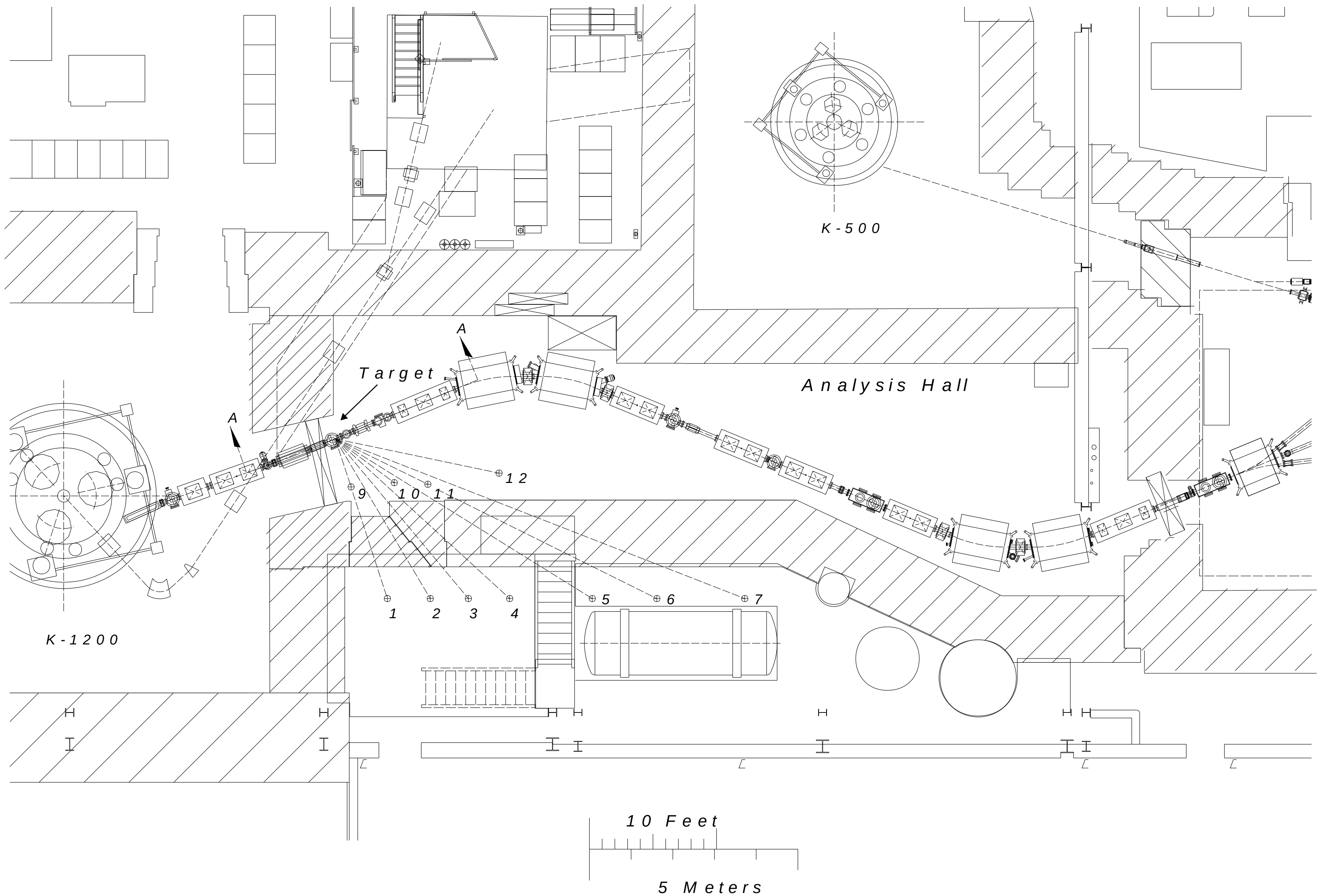
Experiment

- **Experiment performed inside and outside concrete shielding of the A1200 fragment analysis beamline**

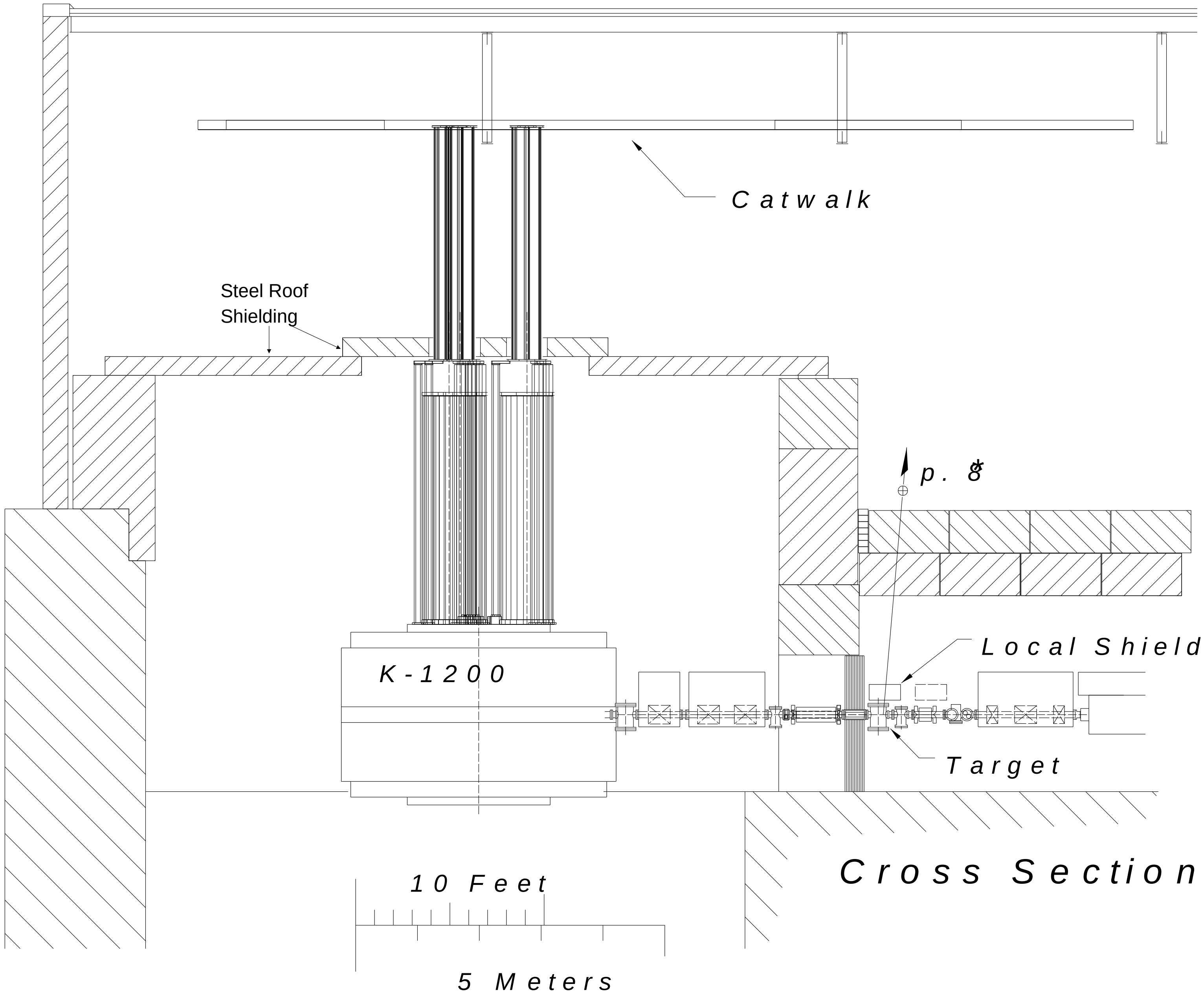
- **Beams:**
  - *^{4}He, ^{12}C, and ^{16}O ions having 155 MeV/u*

- **Stopping Target:**
  - *Hevimet beam stop (95% W, 3.5% Cu, 1.5% Ni)*
  - *Diameter was 5.08 cm and the length was 5.093 cm*
  - *Ranges of Ions in Hevimet:*
    - **4He 1.72 cm**
    - **12C 0.61 cm**
    - **16O 0.46 cm**

- **Normalize by:**
  - *Current Integration*
  - *Monitor detector (plastic scintillator) placed outside of shielding*



K-500
Analysis Hall
Target
A
A
K-1200
1
2
3
4
5
6
7
9
10
11
12
10 Feet
5 Meters



Cross Section A - A

NSCL Bonner Spheres

- 4 mm x 4 mm LiI(Eu) Detector
- Special iron housing (can be used in moderately sized magnetic fringe fields)
- Moderators: none, Cd shield over bare detector, 2-inch, 3-inch, 5 –inch, 8-inch, 10-inch, 12-inch, pseudo-18-inch spheres
- Local preamp, power supply, monitor detector
- Remote MCA, scalers

Bonner Spheres

- **6LiI(Eu) detector, polyethylene moderator spheres having different diameters**

$$C_r = \int_{E_{\min}}^{E_{\max}} \frac{dN}{dE} R_r(E)\, dE$$

  - ***Fredholm integral equation***
  - ***C_r is the observed counting rate in the r-th detector/sphere***
  - ***dN/dE is the differential neutron flux density***
  - ***R(E) is the (known) energy dependent response function of the r-th detector/sphere***

- **Discrete Approximation to Integral**:

$$C_r = \sum_i \frac{dN}{dE} R_r(E_i) \Delta E_i$$

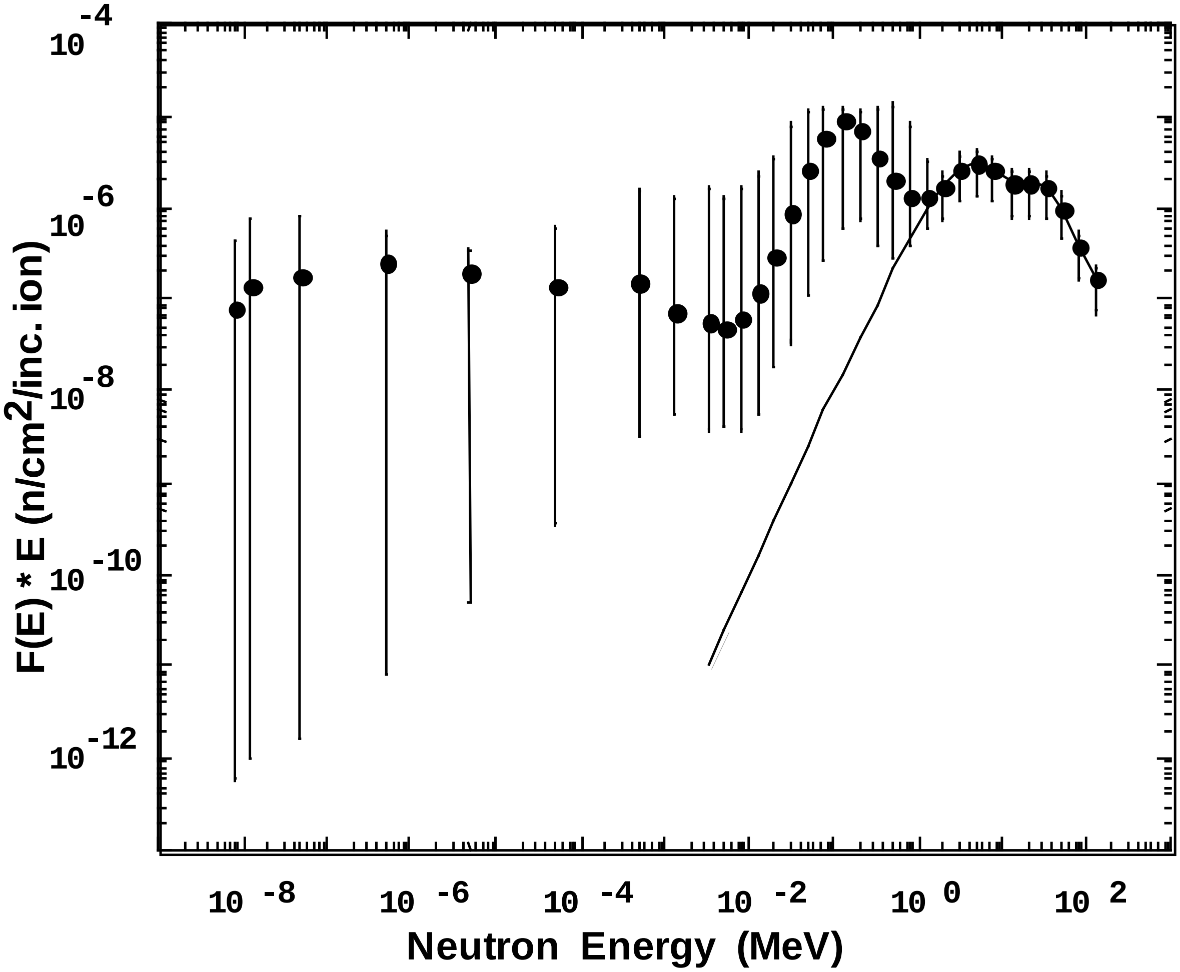
  - ***i labels each member of the set of "energy groups"***
  - ***Typically, 31 energy groups and 8 or 9 measurements: Problem is ill-defined!***

Unfolding, Reconstruction Codes

- **Solve by iterative techniques**
- **Solutions can be ill-behaved**
- **Computer codes:**
  - ***BUNKI (BUNKIUT) iterative recursion***
  - ***LOUHI82 least squares***
  - ***BONDI-97 Genetic Algorithm (Bhaskar Mukherjee, ANSTO)***
  - ***PREF Tikhonov's regularization (Protvino)***
  - ***MAXED Maximum Entropy Deconvolution (Paul Goldhagen, Marcel Reginatto, DOE-EML)***
- **Need *a priori* spectrum**
  - ***Outside of shielding: "1/E" spectrum***
  - ***Inside of shielding: Time-of-Flight spectrum, Monte Carlo calculation***
- **Need to Compare Results from Several Codes**
  - ***Used PREF, a priori was 177.5 MeV/u data of Cecil et al.***
  - ***Checks using PREF, BUNKIUT, BONDI-97 agree reasonably well***

Neutron Spectrum Inside the Shielding

- **155 MeV per nucleon ^{12}C stopping in Hevimet**
- **Solid line is from parameterization of the direct field**



Parameterize the Neutron Spectrum

Inside the shielding, $F(E) = \varphi_{direct} + \varphi_{scattered}$

The "direct" spectrum can be expressed by[1]:

$$\frac{d^2\sigma}{dE d\Omega} = \varphi_{direct}(E,\theta) = \sum_{i=1}^{3} A_i (E/T_i^2(\theta)) \exp(-E/T_i(\theta))$$

- ***Evaporation neutrons with nuclear temperature T_1= 2.2 MeV***
- ***Pre-equilibrium emission, temperature T_2,***
- ***Cascade process, temperature T_3,***

Assume $\varphi_{direct}(E,\theta) = \varphi(E)\varphi(\theta)$

Fitting the energy-dependent part:

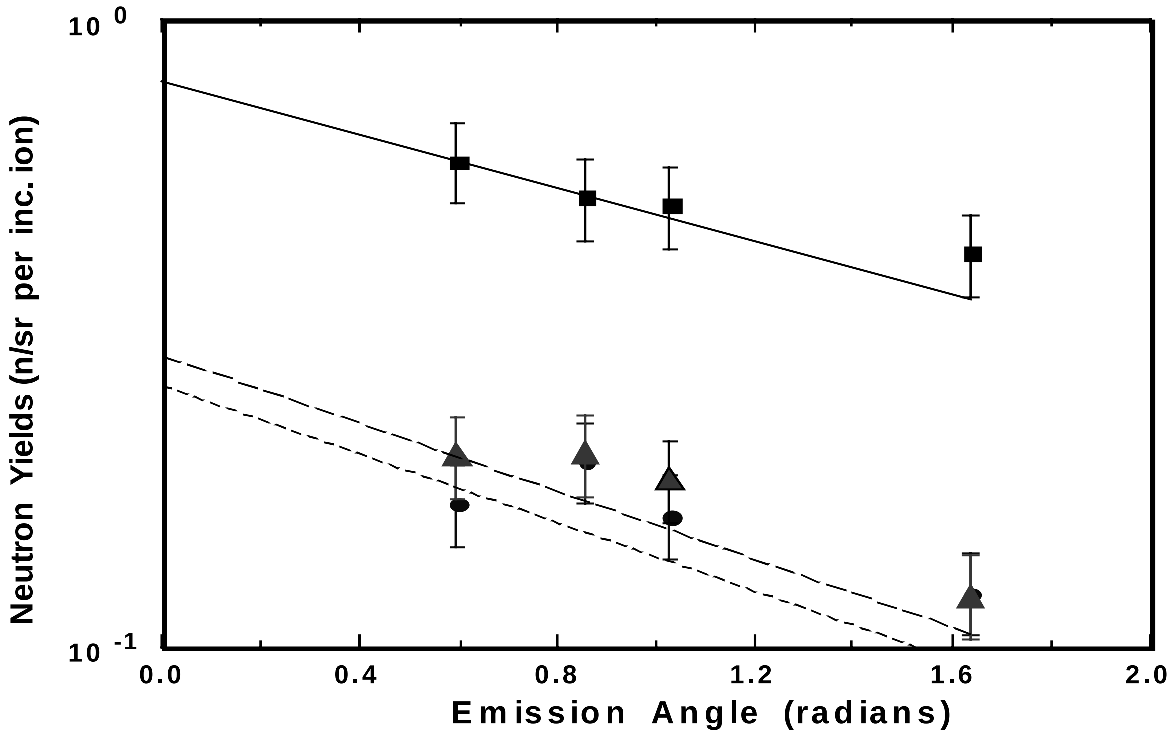
$$\varphi_{direct}(E) = E\left[10^{-2}\exp\left(-\frac{E}{2.2}\right) + 2.4\times10^{-4}\exp\left(-\frac{E}{11.5}\right) + 3.3\times10^{-6}\exp\left(-\frac{E}{36}\right)\right]$$

Parameterize angular distributions of neutron yields:

$$\varphi_{direct}(\theta) = C \times \exp(-\beta\theta)$$

[1] T. Kato and T. Nakamura, "Estimation of neutron yields from thick target by high energy ^{4}He ions for the design of shielding for a heavy ion medical accelerator", Nucl. Instr. Meth. Phys. Res. **A311**, 548-557 (1992). T. Nakamura, "Neutron energy spectra produced from thick targets by light-mass heavy ions", Nucl. Instr. Meth. Phys. Res. **A240**, 207-215 (1985).

Angular Distributions



■ ^{4}He
● ^{12}C
▲ ^{16}O

Neutron Yields

The total neutron yield Y_{total} may be obtained from:

$$Y_{total} = 2\pi \int_0^{\pi} \varphi(\theta) \sin\theta \, d\theta = 2\pi C \frac{(e^{-\beta\pi} + 1)}{(\beta^2 + 1)}$$

Thick-target neutron yields for ^{4}He, ^{12}C and ^{16}O ions having 155 MeV per nucleon:

Angle θ [degrees]	Neutron Yield $\varphi(\theta)$ [neutron / sr / incident ion]		
	^{4}He	^{12}C	^{16}O
34	.596	.169	.202
49	.524	.199	.204
59	.509	.162	.185
94	.425	.122	.121
C and β values, from fitting to Equation 4:			
C [n / incident ion]	.80	.26	.29
β [sr^{-1}]	.49	.51	.51
Total neutron yields [neutrons / incident ion]:			
	4.90	1.56	1.74

"Moyer Model[1]" Approach

Assume the dose-equivalent due to neutrons penetrating a thick shield is proportional to the high-energy particle fluence, h(E$_p$), and the amount of shielding present, by:

$$\mathrm{H}(E_p, \theta, d/\lambda) = \frac{h(E_p)}{r^2} \exp(-\beta\theta) \times \exp(-d(\theta)/\lambda)$$

- ***θ and r are the angle and distance, respectively, between the beam direction and the "neutron detector"***
- ***β is a constant***
- ***d(θ) is the effective shielding thickness at angle θ***
- ***λ is the attenuation length for neutrons in the shielding material***

For 4He:

- First, we note the angular distributions have a shallow slope. Then, $\frac{(e^{-\beta\pi}+1)}{(\beta^2+1)} \approx 1$

$$\mathrm{Y_{total}} = 2\pi\mathrm{C}$$

- The maximum dose equivalent is when $\theta = \frac{\pi}{2}$. This condition allows one to estimate the maximum lateral shielding necessary for some desired dose-equivalent outside of the shielding.

$$\mathrm{H}(r, \frac{d}{\lambda}) = \frac{0.5 \times Y_{total} \times \langle h \rangle}{4\pi r^2} \exp(-\frac{d}{\lambda})$$

[1] B.J. Moyer, Evaluation of Shielding Required for the Improved Bevatron, Lawrence Radiation Laboratory Report UCRL-9769, June, 1961. B.J. Moyer, Method of Calculating the Shielding Enclosure of the Bevetron, in *Premier Colloque International sur la Protection Apres des Grands Accelératuers* (Presses Universitaires de France, Paris, 1962), p.65.

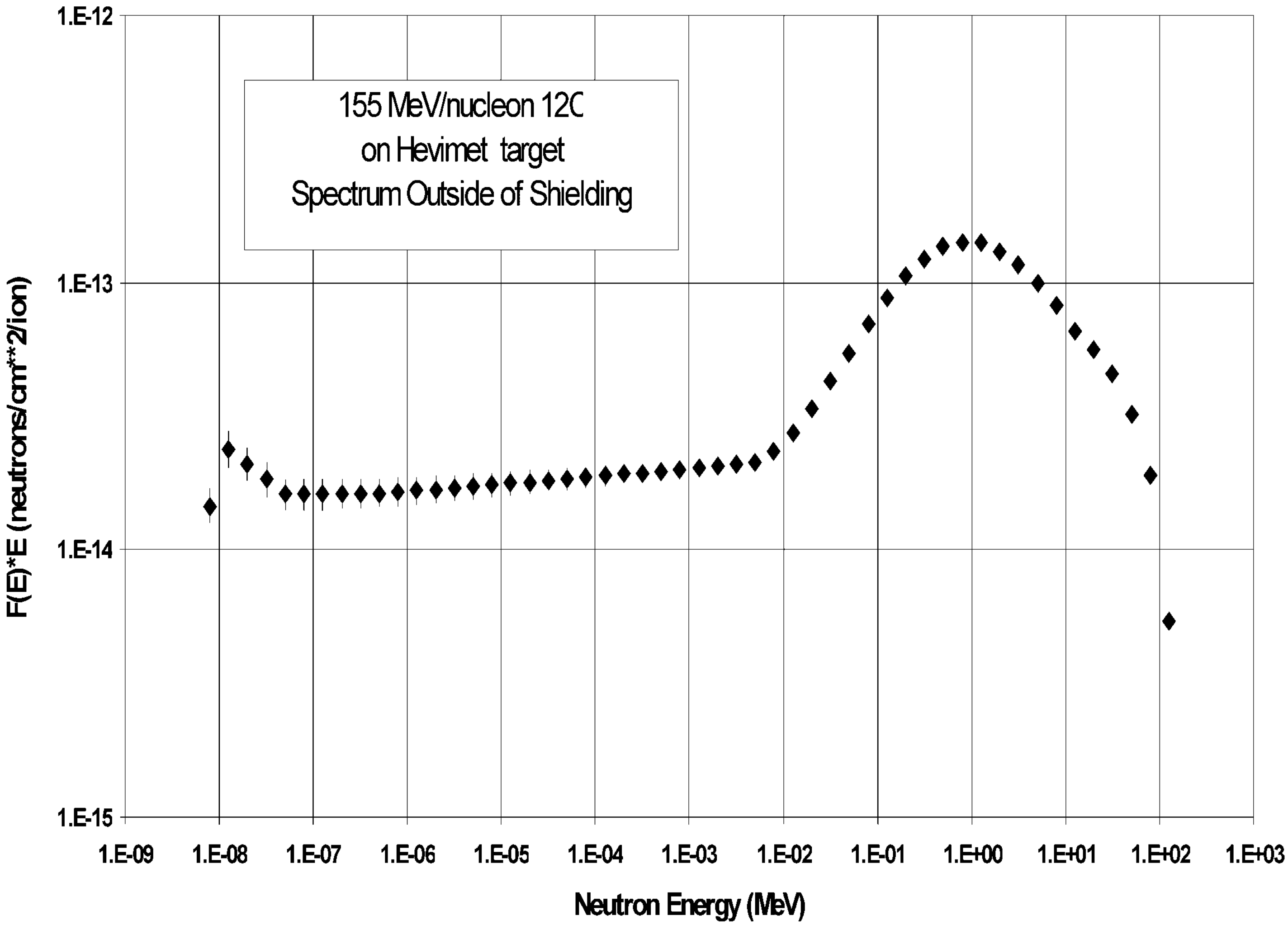
“Moyer” Approach--continued

- **$0.5Y_{total}$ -- neutron yield from pre-equilibrium emission and cascade processes**
- **Use the fluence-to-dose equivalent conversion factor**
  - **<h>= 4.5×10^{-10} Sv-cm^2/neutron for <E> = 30 MeV, the average neutron energy for φ_{casc}**
- **Estimate λ using data for point 1:**
  - **H(point 1, ^{4}He ions) = 1.69×10^{-19} Sv/ion**
  - **r = 403 cm**
  - **d = 308 g/cm^2**
  - **Y_{total} = 4.9 neutrons/ion**
- **We obtain λ = 38 g/cm^2**
- **Finally,**

$$\mathrm{H}(r,d) = \frac{0.5 \times Y_{total} \times 4.5 \times 10^{-10}}{4\pi r^2} \exp(-\frac{d}{38}) \, [\mathrm{Sv/ion}]$$

This equation is now useful for shielding design.

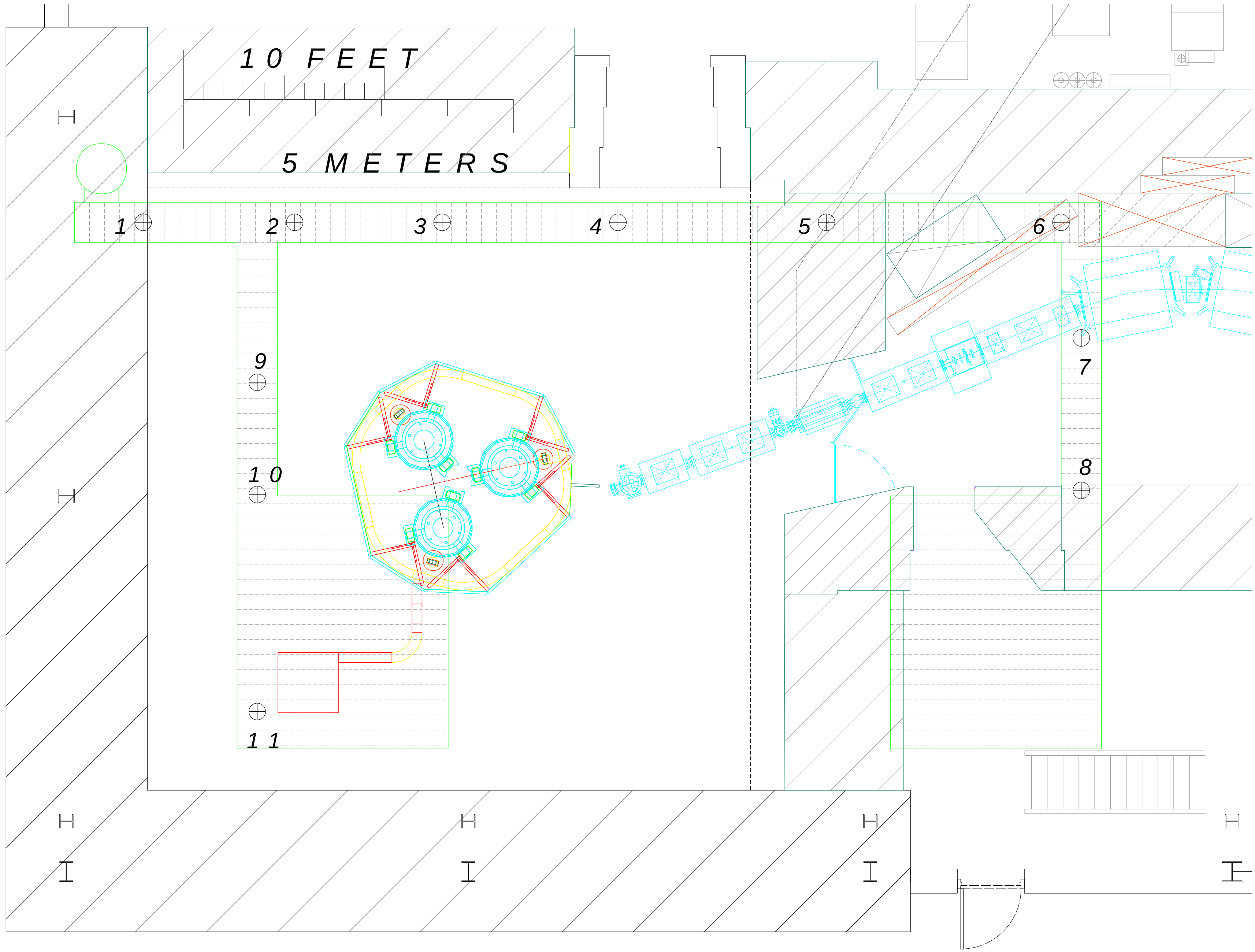
Neutron Spectrum outside the Shielding



Results Outside the Concrete Shielding

Integral characteristics of the neutron fields outside of the K1200 cyclotron shielding for ^{12}C ions.

Point	<E> [MeV]	<h> [Sv cm^2]	F [neutron/cm^2-ion]	H [Sv/ion]
1	3.11	1.91E-10	6.51E-10	1.24E-19
2	3.11	1.91E-10	5.64E-10	1.08E-19
3	3.11	1.91E-10	5.39E-10	1.03E-19
4	1.00	1.70E-10	3.76E-10	6.39E-20
5	.350	8.00E-11	2.41E-10	1.93E-20
6	.300	7.50E-11	1.51E-10	1.13E-20
7	.300	7.50E-11	1.10E-10	8.23E-21
8	.300	7.50E-11	3.19E-10	2.39E-20
8*	.160	5.20E-11	3.27E-10	1.70E-20



10 FEET
5 METERS
1
2
3
4
5
6
7
8
9
10
11

Results Outside of Iron Shielding

Integral characteristics of the neutron fields above the K1200 cyclotron roof for ^{4}He ions.

Point	<E> [MeV]	<h> [Sv cm^2]	F [neutron/cm^2-ion]	H [Sv/ion]
1	3.17	1.32E-10	1.28E-09	1.69E-19
1T	5.70E-02	2.91E-11	9.52E-09	2.77E-19
2T	5.70E-02	2.91E-11	1.42E-08	4.12E-19
3T	5.70E-02	2.91E-11	1.61E-08	4.67E-19
4T	5.70E-02	2.91E-11	1.56E-08	4.53E-19
5T	5.70E-02	2.91E-11	1.33E-08	3.87E-19
7T	5.70E-02	2.91E-11	6.71E-09	1.95E-19
9T	5.70E-02	2.91E-11	2.51E-08	7.30E-19
10T	5.70E-02	2.91E-11	2.54E-08	7.39E-19
11T	5.70E-02	2.91E-11	1.76E-08	5.11E-19

Motivation for Additional Inside-Shield Measurements

- **Few data sets available for thick-target neutron yields, especially for heavy beams**

- **Experiments at the NSCL are predicted to spend more time using heavy (A > 30) ion beams**

  - **When we started (late 1993): Many experiments, much accelerator time devoted to beams such as 12C, 14N, 16O, 18O, 22Ne**

  - **At present, expect large demand for Ar, Kr, Xe beams**

- **How does one assess shielding in this case?**

  - **G.I. Britvich, L.H. Heilbronn, R.M. Ronningen, and P. Rossi**

Measurements Inside of Shielding in Support of the NSCL's Coupled Cyclotron Facility

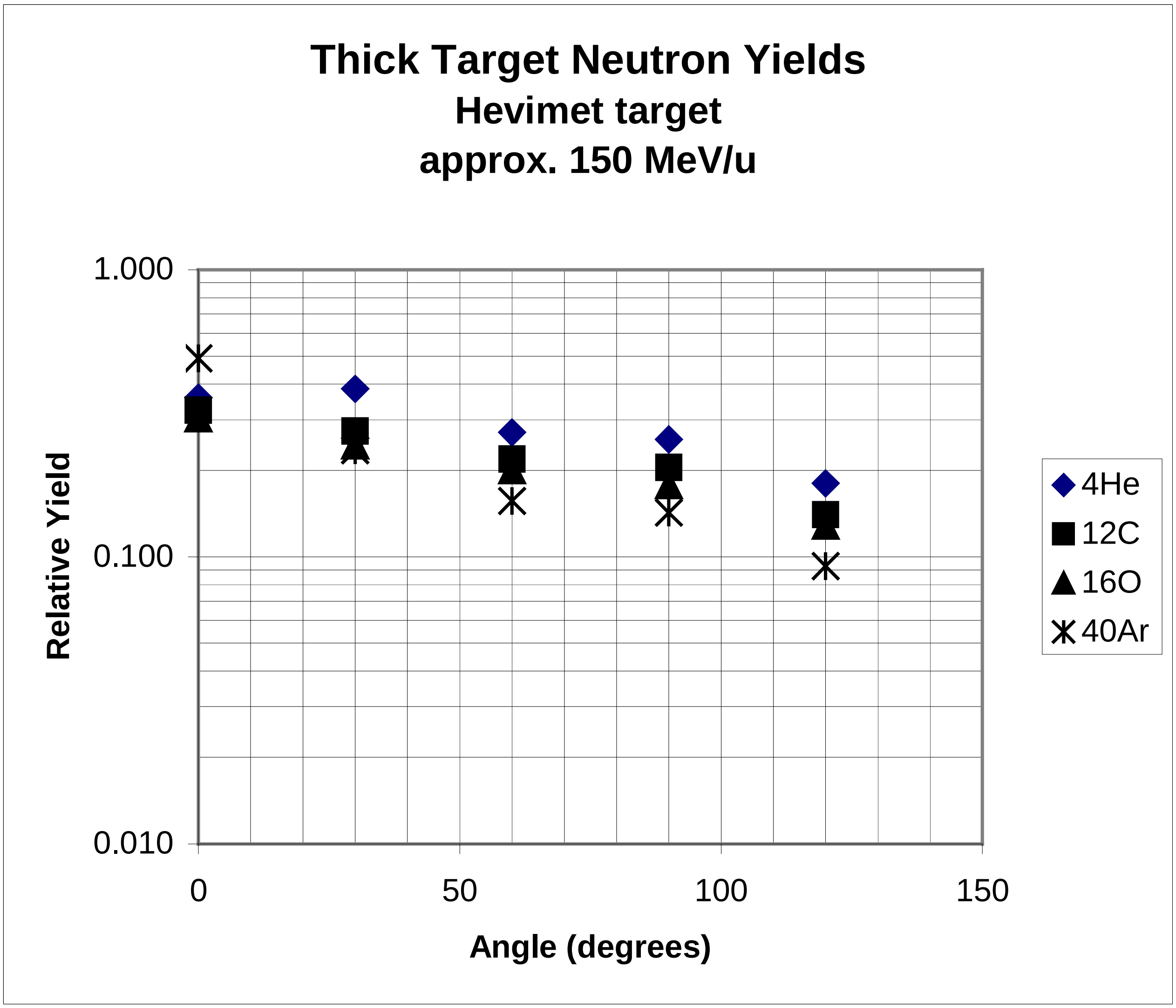
- **Beams:**
  - *^{4}He, ^{12}C, and ^{16}O ions having 155 MeV/u*
  - *^{40}Ar ions having 150 MeV/u*
- **Stopping Target:**
  - *Solid cylinder of Hevimet*
  - *Diameter was 5.08 cm and the length was 5.093 cm*
  - *Ranges of Ions in Hevimet:*
    - **4He 1.72 cm**
    - **12C 0.61 cm**
    - **16O 0.46 cm**
    - **^{40}Ar 0.20 cm**
- **Current Integration:**
  - *The target was pressed into a long copper pipe. Insulating rings were placed around this pipe, and the assembly was placed in the beam line, forming a Faraday cup.*
  - *Monitor detector (plastic scintillator) also used, at 2 meters and 20 degrees*

Details

- **Detectors**
  - ***Commercial Bonner-sphere spectrometer, having polyethylene spheres with diameters of 2, 3, 5, 8, 10, and 12 inches.***
  - ***Additionally:***
    - **"bare" detector, i.e., without using a sphere**
    - **bare detector covered with cadmium foil**
    - **For the ^{40}Ar measurements, a cylinder of polyethylene, having 18 inches in length and 17 inches in diameter, was used as an 18-inch pseudo-sphere**
  - ***The detector was a cylinder (4 mm diameter, 4 mm length) crystal of LiI(Eu), enriched in ^{6}Li, mounted to a photomultiplier tube.***
  - ***The detector-photomultiplier housing was constructed of low-carbon steel, for additional magnetic shielding.***
- **One-meter Distance from Target**
- **Angles**
  - ***0, 30, 60, 90, and 120 degrees, with respect to the beam direction***

Preliminary Results

- **Data unfolded using BUNKIUT**
  - ***Sanna matrix***
  - ***“1/E” a priori spectrum***



Preliminary Results

- Neutron yields from ion beams of ^{4}He, ^{12}C, ^{16}O at 155 MeV/u, and ^{40}Ar at 150 MeV/u.
- The number of neutrons per ion is shown for two different energy cuts, and is compared to the previous measurement.

Ion	Neutrons/ion E > 0 MeV	Ratio to He	Neutrons/ion E > 4 MeV	Ratio to He	Compare to Britvitch *et al.*	Ratio to He
^{4}He	3.1	1.00	1.0	1.0	4.9	1.00
^{12}C	2.4	0.78	0.79	0.8	1.56	0.32
^{16}O	2.2	0.69	0.72	0.7	1.74	0.36
^{40}Ar	1.6	0.52	0.46	0.5		

Corrections to Make

- **Target Self-Shielding**
  - ***Measurements with Beam***
    - **90 degrees**
    - **Measurements using the beam were made first with the target alone, then with additional Hevimet.**
  - ***Measurements using a PuBe source (about 4.5 MeV average neutron energy)***
    - **first with the target removed and then with the source behind the target.**
  - ***Both sets of measurements, using the data for the three largest spheres, gave an estimation of the average interaction length of about 1.27 cm.***
- **Room Scattering**
  - ***"Shadow Bar"***
    - **Cylinder of iron, having a diameter of 10.16 cm and a length of 30.48 cm, placed between the target and the spectrometer at 90 degrees.**
  - ***PuBe source + Shadow Bar***
    - **Truncated cone of brass, 27.94 cm-long, tapered from 17.15 cm in diameter to 10.80 cm**
    - **Placed at zero degrees**

Can We Make Estimates?

- **We try to make estimates using the experimental data of Heilbronn *et al. (Nucl. Sci. Eng. 132, 1(1999)):***

System (155 MeV/u)	Yield (Neutrons/ion)	Interaction Fraction	Multiplicity (Neutrons/interaction)
^{4}He + Al	0.348(13)	0.34	1.02(4)
^{12}C + Al	0.179(5)	0.18	0.99(3)

- **Approach:**
  - ***Use a known multiplicity or yield***
  - ***Calculate ratios of multiplicities (unknown/known)***
  - ***Calculate the number of interactions***
  - ***Estimate the unknown yield***

Approach

After Madey *et al.*

- ***R. Madey, B.D. Anderson, R.A. Cecil, P.C. Tandy, and W. Schimmerling, Phys. Rev. C 28, 706(1983):***

- ***Ratio of Multiplicities for two different beams on the same target:***

$$R = \frac{M\left(A_1, Z_1, A_t, Z_t, \frac{E}{A}\right)}{M\left(A_2, Z_2, A_t, Z_t, \frac{E}{A}\right)} = \frac{\sigma\left(A_1, Z_1, A_t, Z_t, \frac{E}{A}\right)}{\sigma\left(A_2, Z_2, A_t, Z_t, \frac{E}{A}\right)} \times \left(\frac{A_1^{1/3} + A_t^{1/3}}{A_2^{1/3} + A_t^{1/3}}\right)^5$$

- ***Calculate interacting fractions:***

$$Interaction\ \ fraction = -\frac{6.022 \times 10^{23}}{A_t} \times \int_0^E \frac{\sigma\left(A_i, Z_i, A_t, Z_t, \frac{E}{A}\right)}{\frac{dE}{d\rho x}} dE.$$

- **We used total reaction cross sections parameterized by Kox *et al.* and Townsend and Wilson:**
  - o ***L.W. Townsend and J.W. Wilson, Phys. Rev. C 37, 892(1988)***
  - o ***S. Kox et al., Phys. Rev. C 35, 1678 (1987)***

Predictions

Estimates of neutron yields from thick targets for beams available from the NSCL's Coupled Cyclotron Facility, relative to carbon:

Ion	Reactions per Ion	Yield/Inc. Ion at 155 MeV/u	Ratio of Yields Compared to ^{12}C
^{12}C	0.224	0.18	1.0
^{18}O	0.224	0.21	1.2
^{22}Ne	0.189	0.19	1.1
^{36}Ar	0.115	0.14	0.8
^{48}Ca	0.139	0.19	1.1
^{84}Kr	0.096	0.18	1.0

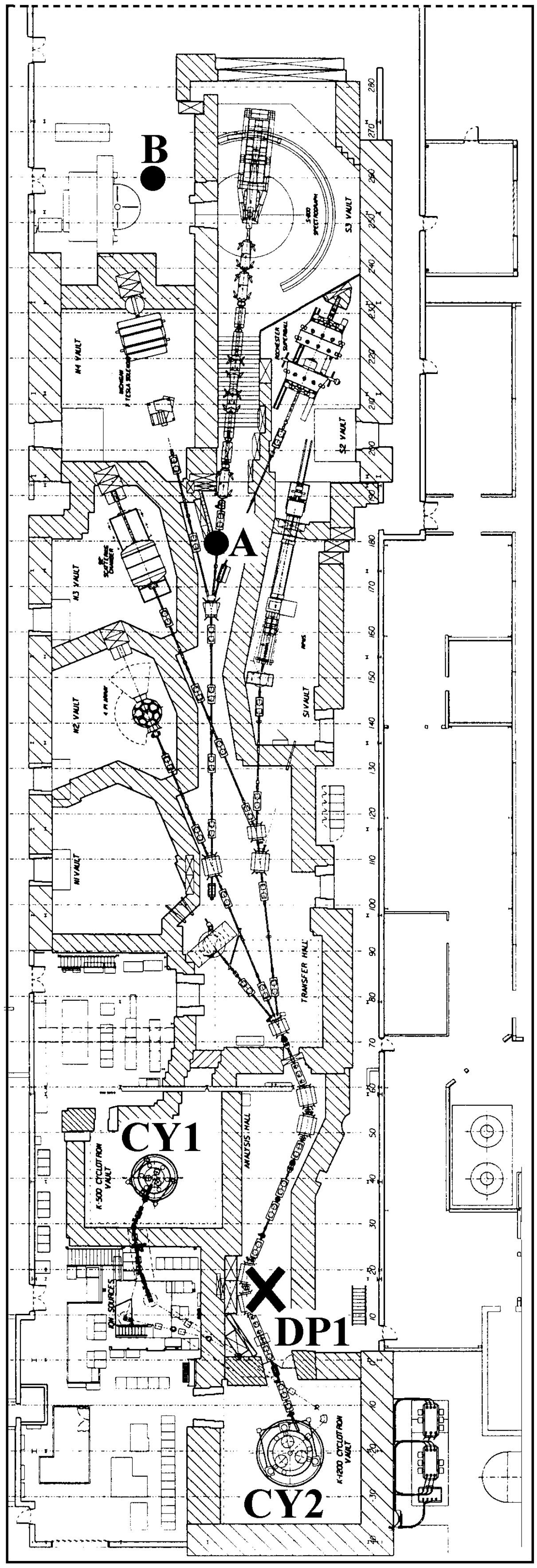
- **Compare 36Ar/12C ratio of 0.8 to experimentally determined 40Ar/12C ratio of 0.6 – 0.7.**

- **Reasonable agreement**

Skyshine Measurements at the NSCL

- **Measurements of skyshine were made at the NSCL**
  - **R.M. Ronningen, B. Mukherjee, and P. Rossi**
- **Source of skyshine neutrons:**
  - ***Region of the A1200 fragment mass separator where the beam is dumped***
- **Measure:**
  - ***Total dose equivalent at reference point***
  - ***Average neutron energy***
  - ***Neutron spectrum***
  - ***Dose equivalents at 25, 50, 75, 100, and 110 meters from reference point***
- **Using:**
  - ***Bonner sphere set***
  - ***Eberline NRD neutron rem meter***
- **Three Beams**
  - ***100 MeV/u 13C, 100 MeV/u 20Ne, 140 MeV/u 4He***

NSCL Floor Plan

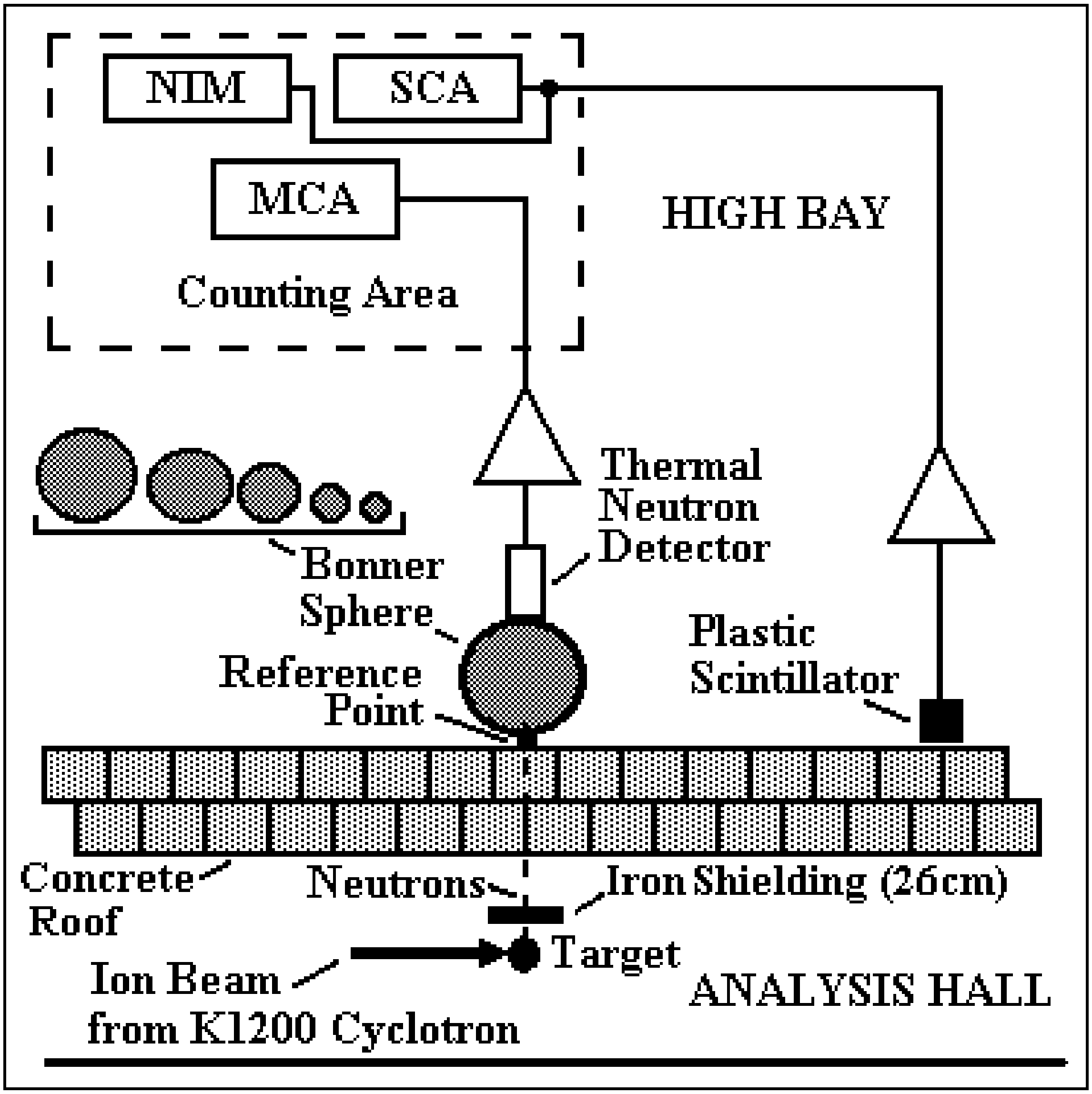


Bubble Dosimeters

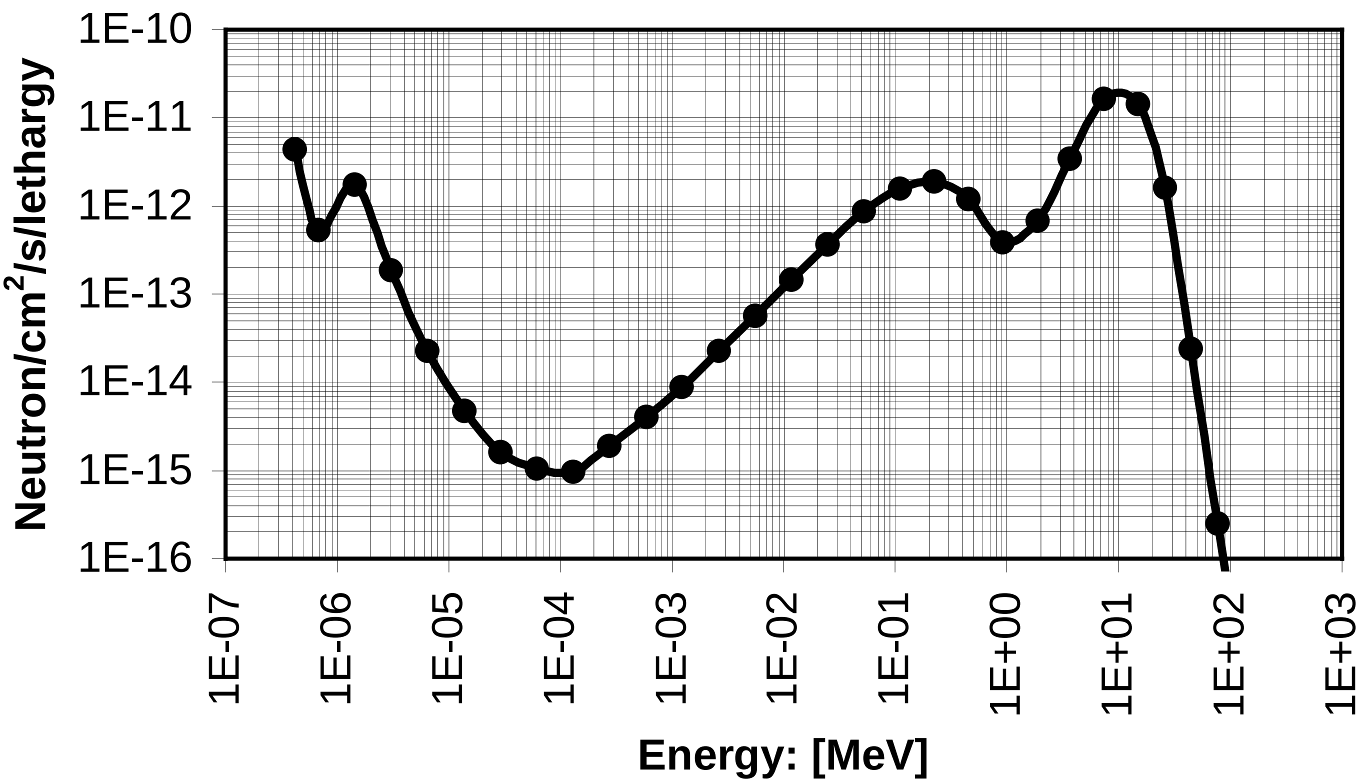
▲ ***BD-100R neutron "bubble" dosimeters***

- **Obtained from Bubble Technology Industries, Chalk River, Canada**
- **Reusable, integrating passive dosimeters**
- **Elastic polymer throughout which droplets of superheated liquid have been dispersed**
- **When these droplets are struck by neutrons, they form small gas bubbles that remain fixed in the polymer**
- **Visible detection of neutron radiation**
- **Real-time dose determination**
- **The detector response in independent of dose rate and is tissue equivalent.**
  - **Sensitivities of 22 and 47 bubbles per millirem The 22-bubbles/mrem dosimeters were used at 25 and 50 meters.**
  - **The 47-bubbles/mrem dosimeters were used at the other distances. Two of these were used at 115 m and the results were averaged.**

Schematic of Setup



Skyshine Source Neutron Spectrum



- **Neutron energy spectrum at the reference point during the bombardment of the aluminum stopping bar with the 140 MeV/nucleon ^{4}He ions in the Analysis Hall.**
- **The average neutron energy was determined to be 2.5 MeV.**

Bubble Dosimeters

▲ ***BD-100R neutron "bubble" dosimeters***

- **Obtained from Bubble Technology Industries, Chalk River, Canada**
- **Reusable, integrating passive dosimeters**
- **Elastic polymer throughout which droplets of superheated liquid have been dispersed**
- **When these droplets are struck by neutrons, they form small gas bubbles that remain fixed in the polymer**
- **Visible detection of neutron radiation**
- **Real-time dose determination**
- **The detector response in independent of dose rate and is tissue equivalent.**
  - **Sensitivities of 22 and 47 bubbles per millirem The 22-bubbles/mrem dosimeters were used at 25 and 50 meters.**
  - **The 47-bubbles/mrem dosimeters were used at the other distances. Two of these were used at 115 m and the results were averaged.**

Photo of Exposed Bubble Dosimeter

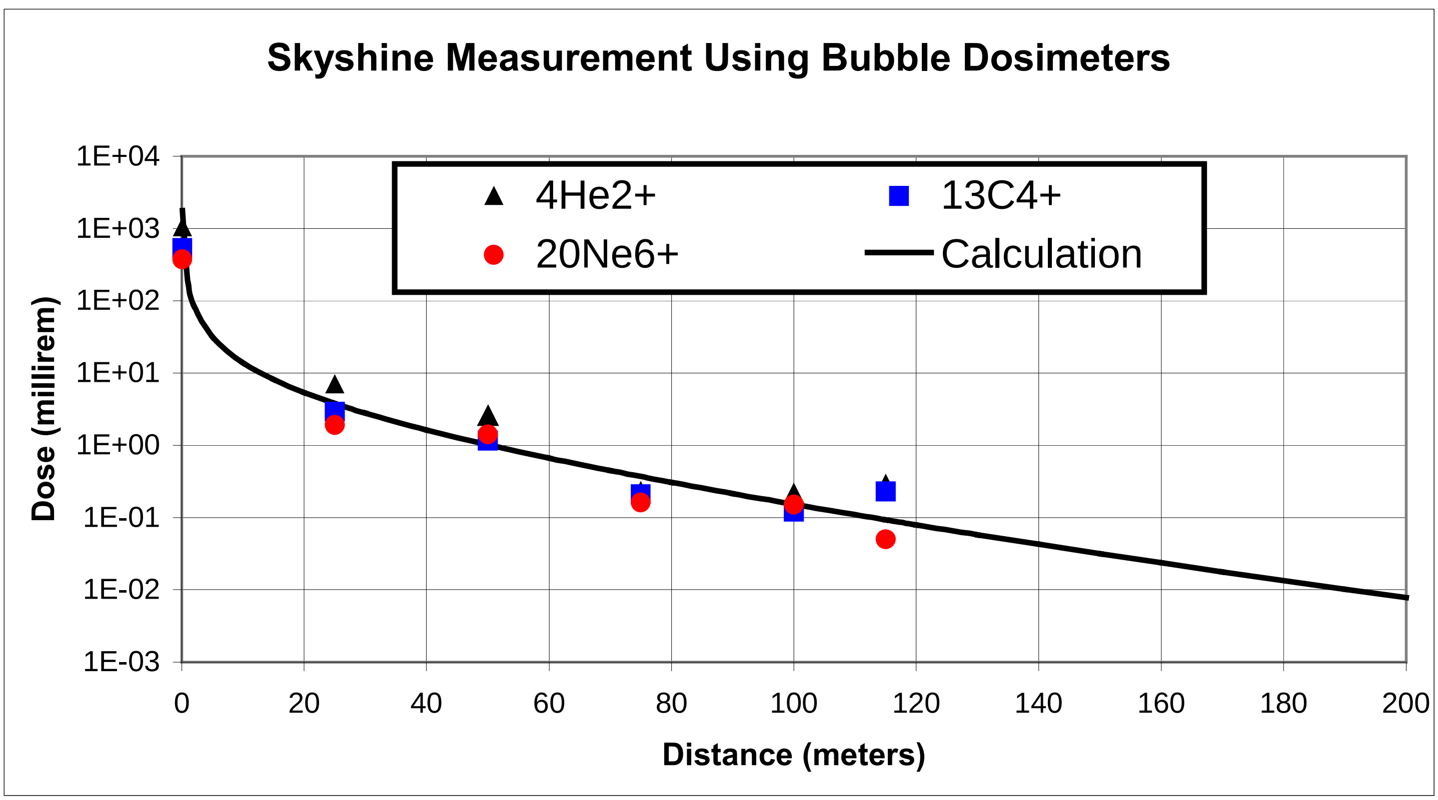
- **BDR 100 Characteristics:**

  - **Energy Range: < 200 keV to > 15 MeV**
  - **Dose range: 1 – 5000 μSv (0.1 – 500 mrem)**
    - **Sensitivity: typical is 0.033 – 33 bubbles/μSv (0.33 – 33 bubbles/mrem at 20 degrees Celsius, with an accuracy of ± 20% when calibrated by an ^{241}AmBe neutron spectrum).**
  - **Temperature range: 10 – 35 degrees C. Can be obtained with temperature compensation.**
  - **Tissue equivalent**
  - **Gamma insensitive**
  - **Isotropic**
  - **Can be reused (about US$65 each)**

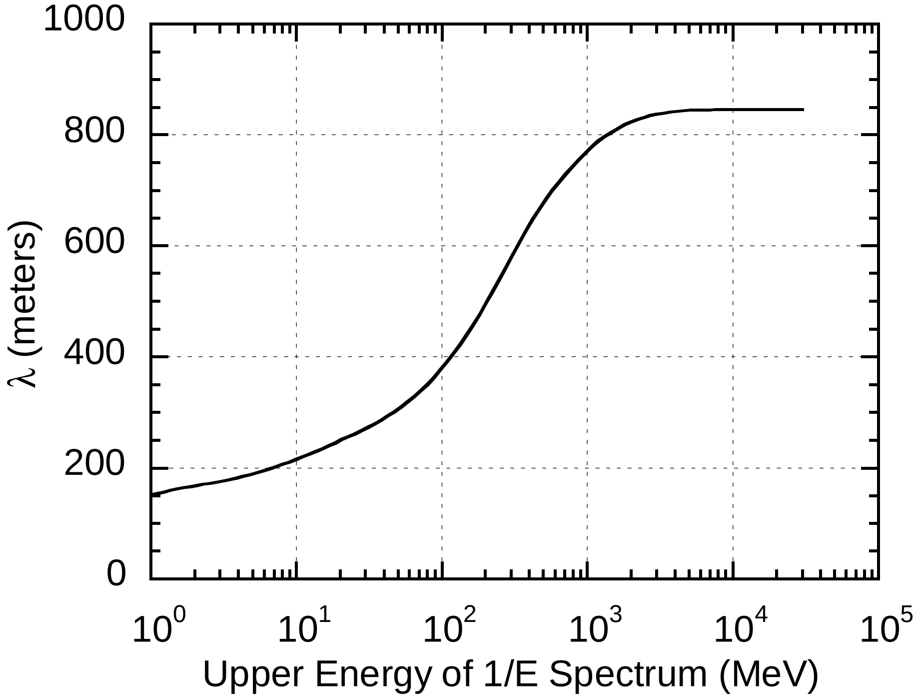
Skyshine Measurement Results

- **Patterson and Thomas formula:** $\phi = \frac{aQ}{4\pi r^2} e^{-r/\lambda}(1-e^{-r/\mu})$
- **Build-up relaxation length in air (λ) fixed at 56 meters.**
- Calculation:

$$H(mrem) = \frac{1.45x10^5}{4\pi\, r^2} e^{-r/64.3}(1-e^{-r/56})$$



Effective Absorption Length



Effective absorption length λ as a function of

upper neutron energy *E* for *1/E* spectra.

[Adapted from G. R. Stevenson and R. H. Thomas, "A simple procedure for the estimation of neutron skyshine from proton accelerators", Health Phys. 46 (1984) 115-122.]

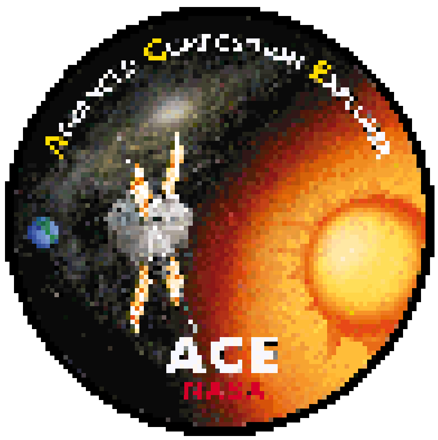
- **Small value of λ (~ 64 meters) consistent with neutron spectrum having small average energy (~ 2.5 – 5 MeV)**

Summary

- Characterized the skyshine source spectrum
- Measured skyshine
    - Bubble dosimeters cheap alternative to electronically-read, moderated detectors such as the DePangher Long Counter
- Used classic equation to describe results
- Use operations matrix to predict doses for different beams, varying times, distances, site boundaries *etc*.

NSCL Support of Space Science

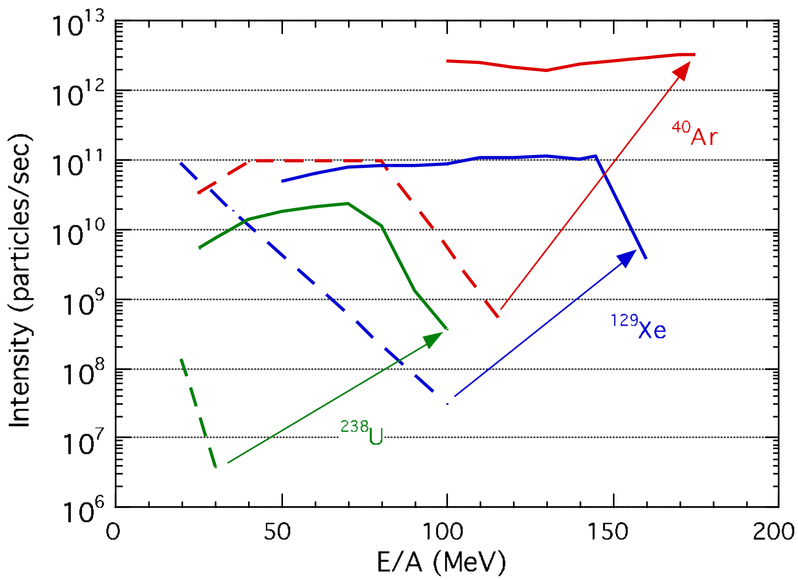
- Calibrations of Advanced Composition Explorer instruments



- Test charged particle response of CsI calorimeter detector prototypes for GLAST

- NASA-supported beamline for Single Event Effects Research

Coupled Cyclotron Facility (CCF) Capabilities



The figure above shows the performance of the K1200 cyclotron in stand-alone mode (dash-lines) compared to when the K500 and K1200 cyclotrons operated in a coupled mode (solid lines).

Large radioactive-ion-beam intensity gains result:

	^{11}Li	**^{19}Ne**	**^{32}Mg**	**^{56}Ni**	**^{132}Sn**
K1200 Stand-Alone Operation	2.5×10^{3}	6×10^{7}	1.2×10^{3}	7×10^{4}	2
CCF	4×10^{6}	1×10^{10}	3×10^{6}	4×10^{8}	4×10^{4}
Gain	**1.6×10^{3}**	**1.7×10^{2}**	**2.5×10^{3}**	**5×10^{3}**	**2×10^{4}**